(Vector) Meson Production and Duality

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Abstract. At high enough energies, hadronic cross sections, if averaged over an appropriate energy range, must coincide with a perturbative QCD description. One famous example in deep inelastic scattering is termed Bloom-Gilman duality. This quark-hadron duality shows that the nucleon resonance region closely mimics the deep inelastic region where we assume single quark scattering to be dominant. This Bloom-Gilman duality was recently found to work to high precision to far lower momentum transfers, and far smaller regions in invariant mass, than anticipated. Implications for using the spin/flavor selectivity of (polarized) electron-proton scattering and/or (polarized) meson electroproduction to examine such duality in more detail are discussed.

I INTRODUCTION

Three decades ago, Bloom and Gilman observed a fascinating correspondence between the resonance electroproduction and deep inelastic kinematic regimes of inclusive electron-nucleon scattering [1,2]. Specifically, it was observed that the resonance strength could be related to the deep inelastic strength via a scaling variable which allowed the comparison of the lower missing mass squared, W^2, and lower four-momentum squared, Q^2, resonance region data to the higher W^2 and Q^2 deep inelastic data. Further, this behavior was observed over a range in Q^2 and W^2, and it was found that, with changing Q^2, the resonances move along, but always average to, the smooth scaling curve typically associated with deep inelastic scattering. This behavior clearly hinted at a common origin for resonance (hadron) electroproduction and deep inelastic (partonic) scattering, termed quark-hadron, or Bloom-Gilman, duality.

A global kind of quark-hadron duality is well established: low-energy resonance production can be shown to be related to the high-energy behavior of hadron-hadron scattering [3]; the familiar ratio of $e^+e^- \rightarrow$ hadrons over $e^+e^- \rightarrow$ muons uses duality to relate the hadron production to the sum of the squared charges of the quarks: here duality is guarantueed by unitarity [4]; in Perturbative QCD (PQCD) the high-momentum transfer behavior of nucleon resonances can be related to the high-energy transfer behavior of deep inelastic scattering [4,5]. Poggio, Quin, and Weinberg [6] suggested that inclusive hadronic cross sections at high energies, averaged over an appropriate energy range, had to approximately coincide with a quark-gluon perturbation theory. However, in general, it is not clear why duality should also work in a localized region, and even at relatively low momentum transfers.

II INCLUSIVE SCATTERING

Inclusive deep inelastic scattering on nucleons is a firmly-established tool for the investigation of the quark-parton model. At large enough values of W^2 ($= M^2 + Q^2(1/x$ - 1), with M the proton mass and x the Bjorken scaling variable) and Q^2, QCD provides a rigorous description of the physics that generates the Q^2 behavior of the nucleon structure function $F_2 = \nu W_2$. The well-known logarithmic scaling violations in this structure function, predicted by asymptotic freedom, played a crucial role in establishing QCD as the accepted theory of strong interactions [7,8].

An analysis of the resonance region at smaller W^2 and Q^2 in terms of QCD was presented in Refs. [9,10], where Bloom and Gilman's duality was re-interpreted, and the integrals of the average scaling curves were equated to the n =2 moment of the F_2 structure function. The Q^2 dependence of these moments can be described by ordering the contributing matrix elements according to their twist (= dimension - spin) in powers of $1/Q^2$. It was concluded [9] that the fall of the resonances along a smooth scaling curve with increasing Q^2 was attributed to the fact that there exist only small changes in these lower moments of the F_2 structure function due to higher twist effects. Such effects are inversely proportional to Q^2, and can therefore be large at small Q^2. If not, averages of the F_2 structure function over a sufficient range in x at moderate and high Q^2 are approximately the same.

Recently, high precision data on the F_2 structure function from Jefferson Lab [11] have quantified these earlier observations, and demonstrated that duality works to better than 10% for both the total nucleon resonance region and each of the separate low-lying nucleon resonance regions, for $Q^2 \geq 0.5$ (GeV/c)^2. This is illustrated in Fig. 1, where the nucleon resonance data for various Q^2 is compared to parameterizations of deep inelastic scattering data at constant $Q^2 = 5$ and 10 (GeV/c)^2 [12]. Such behavior shows that the distinction between the nucleon resonance region and the deep inelastic region is spurious; if properly averaged, the nucleon resonance regions closely mimic the deep inelastic region.

Even more surprising, it was found that the nucleon resonance region data *at all* Q^2 oscillate around a single smooth curve, as shown in Fig. 2. This curve coincides with the deep inelastic scaling curve at $Q^2 > 0.5$ (GeV/c)^2, consistent with Bloom-Gilman duality, and resembles neutrino/anti-neutrino xF_3 data or a valence-like sensitivity only [13] below $Q^2 \approx 0.5$ (GeV/c)^2. This is perhaps not too surprising in the quark model where the nucleon resonances act as valence quark transitions, while at low Q^2 not many sea quarks can be "seen" yet. However, it is surprising that all the strongly-interacting nucleon resonances shuffle their strength around as function of Q^2 to closely follow a single scaling curve. Do we see duality down to the lowest values of Q^2?

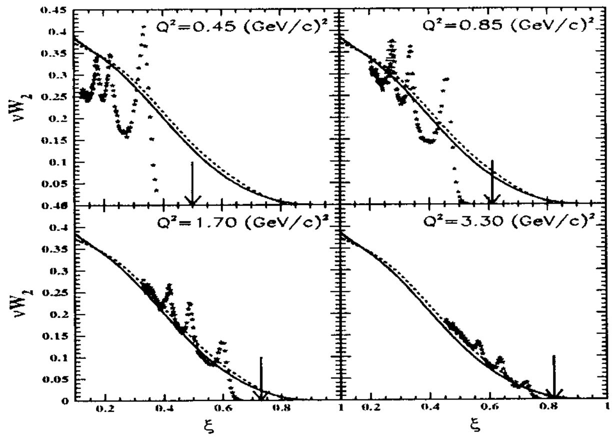

FIGURE 1. Sample hydrogen νW_2 structure function spectra obtained at $Q^2 = 0.45, 0.85, 1.70,$ and 3.30 $(\mathrm{GeV/c})^2$ and plotted as a function of the Nachtmann [14] scaling variable ξ. Arrows indicate elastic kinematics. The solid (dashed) line represents the NMC fit of deep inelastic structure function data at $Q^2 = 10$ $(\mathrm{GeV/c})^2$ ($Q^2 = 5$ $(\mathrm{GeV/c})^2$).

Future investigations would fully utilize the spin/flavor selectivity of the electron-proton reaction. E.g., it is well known that, at low Q^2, the $N - \Delta$ quark model transition contributes negatively to the polarized structure function g_1. Does duality only work if one averages over a large enough invariant mass region to provide positive definite results? Do the polarized structure functions exhibit a valence-like sensitivity too, similar as the F_2 unpolarized structure function? These questions remain completely unresolved to date.

III SEMI-INCLUSIVE SCATTERING

Duality in the case of semi-inclusive meson photo- and electroproduction has not been experimentally tested. Here duality would manifest itself with an observed scaling in the meson plus resonance final state [15].

Assuming one is in a kinematics region that mimics single-quark scattering, in analogy with the inclusive scattering case, the question here is whether the remaining part of the process can be described in terms of a process where the struck quark hadronizes into the detected meson. Such a factorization approach is strictly valid at asymptotic energies only, as at low energies there may not be clear separation of target and current fragmentation regions [16]. To what extent factorization applies at lower energy is an open question, although recent data supports factorization at lower energies than previously anticipated [17].

However, as in the inclusive case where the nucleon resonances average at low energies to the scaling curve, the nucleon resonances remaining in the final state after having produced a fast meson may also average to the fragmentation function. If duality holds for semi-inclusive scattering, the overall scale of scattering

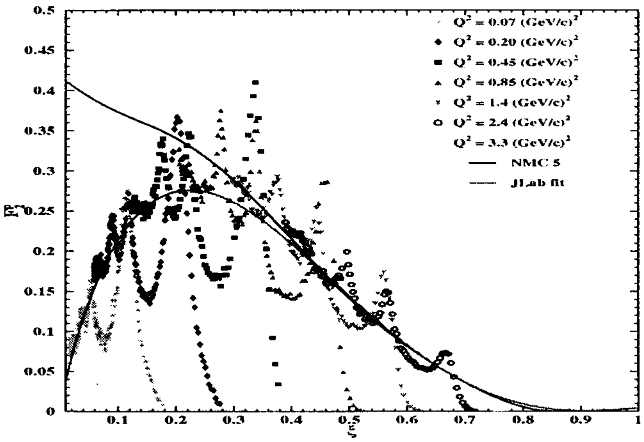

FIGURE 2. Sample hydrogen νW_2 structure function spectra obtained at various Q^2 and plotted as a function of the Nachtmann scaling variable ξ. The data at $Q^2 = 0.07$ and 0.20 (GeV/c)^2 are from older SLAC expriments. The solid line represents the NMC fit of deep inelastic structure function data at $Q^2 = 5$ (GeV/c)^2. The light solid line represents a fit of the various nucleon resonance spectra.

in the low-W' region must mirror that at high W', with W' the invariant mass of the residual system after the meson has been removed. This may come about *if* the various decay channels from resonances with varying W' interfere such that factorization holds. Obviously, this would require a non-trivial interference of these decay channels but this may not be unlikely if one realizes that duality has also been observed in hadronic τ decays [18].

In practice, one can extract the meson yield $\frac{dN^m}{dz}$ over a range of elasticity z (the fraction of total energy transfer ending up in the fast meson) at several values of x and Q^2. This allows the comparison of $\frac{dN^m}{dz}$ in the resonance region to that in the deep inelastic regime, which we obtain from the quark model or from parameterizations of data. Sparse information from both older Cornell data and recent JLab data strongly suggests that of order 10 GeV beam energy will provide the right kinematics region to study the onset of the duality phenomenon in meson electroproduction [19,20].

If so, one could perform a systematic study of duality for current fragments and target fragments with an energy of order 200 GeV. At such energies, a clear separation between current and target fragmentation regions exists [16], enabling a precise investigation of duality in the current fragmentation region with various meson or baryon tags, in addition to an investigation of duality in the target fragmentation region. In order to shed light on the transition from strongly-interacting matter to Perturbative QCD, one must understand the origin of duality. To accomplish this, it must be determined what energy region one has to average over, and what energies one needs to reach, such that hadronic processes equal a perturbative quark-gluon theory.

If one understands duality it may be used as a tool. It can give guidance to cuts typically used to select "hard scattering" regions. E.g., it shows that the $W^2 > 4$ cut to select deep inelastic events is spurious. One can access the very large x region, where, without escape, one encounters the nucleon resonance region. This could provide us with data for parton distribution functions in the strict valence region, and allow investigations of the Q^2 evolution of large-x parton distribution functions. One can utilize duality for a complete spin/flavor and valence-sea decomposition of parton distribution functions. Furthermore, using tags of various mesons one can address questions like: Does one enhance sensitivity to sea quarks if one tags with kaons or ϕ's? What are the vector mesons dual to?

Higher energies also enable one to investigate duality for the heavy quark sector, where calculations are more readily performed [21], and to investigate duality between hadrons and jets [22]: here one can argue that a jet similarly comes about by non-trivial interference between the produced hadrons.

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